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Causality and the speed of sound

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Abstract A usual causal requirement on a viable theory of matter is that the speed of sound be at most the speed of light. In view of various recent papers querying this limit, the question is revisited here. We point to various issues confronting theories that violate the usual constraint.

1 Introduction

In cosmology and astrophysics, it is usually assumed that the speed of sound c_s cannot exceed the speed of light c; indeed $c_s > c$ is taken as a criterion for rejecting theories. This is the view put in established texts (see, e.g., Refs. [1,2]), in earlier papers (see e.g. [3]), and in more recent work. For example, it has been argued that accelerating k-essence models in cosmology are ruled out because the scalar field fluctuations in this case must propagate superluminally [4]. Low-energy effective field theories have been rejected when, despite having Lorentz-invariant Lagrangians, they admit superluminal fluctuations [5]. Subluminal propagation of field fluctuations has been imposed as a condition on a relativistic gravitation theory for the MOND paradigm [6,7].

Other recent papers however challenge these standard views of causality (see, e.g., Refs. [8,9,10,11]), and propose matter models that allow superluminal signal propagation, which can lead to interesting effects in cosmological and astrophysical contexts. (These are not the first such models: see e.g. [12, 13].)

Here there is a clash of cultures between an approach where a matter model, usually based on an assumed Lagrangian, can be chosen freely, and an approach where fundamental relativistic principles constrain the matter model. The immediate problem with matter models that have superluminal physical modes is that they may violate causality, one of the most basic principles of special relativity theory. To be specific, many proposals violate “Postulate (a): Local Causality”, given on page 60 of

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Ref. [1]. This is usually taken as a criterion for rejecting a theory, because local causality is taken to be an absolute requirement on all theories:

Comment 1: *The strictly relativistic position is that matter models which violate the causality requirement* $c_s^2 \leq c^2$ *are ruled out as unphysical.*

However there are a number of papers appearing in the current literature that do not take this view. Instead, they drop the usual speed of sound limit on fluid or scalar field models, but maintain special relativity properties locally. To test if the conservative view (as stated in Comment 1) is too restrictive, we look here at some issues that arise from this drastic step. Thus we consider foundational issues which have to be taken into account in any proposal allowing such apparent causality violations. We find that one can indeed construct a macroscopic phenomenological theory that is covariantly well-defined and respects standard principles including Lorentz invariance. However, in such an approach, fundamental features in all of physics (special relativity, electromagnetism, gravitation, quantum field theory, etc.) are determined or affected by an arbitrary matter model. Furthermore, it appears that such matter models cannot be based in a relativistically acceptable microphysical theory.

2 Macroscopic fluid models and the sound cone

Consider a perfect fluid in a Special or General Relativity context, with equation of state $p/c^2 = w\rho$ relating the pressure p to the energy density ρ. If w is constant, the speed of sound is given by

$$\frac{c_s^2}{c^2} = \frac{1}{c^2}\frac{dp}{d\rho} = w\,, \tag{1}$$

and if w is slowly varying, this is still a good approximation. Thus one can get $c_s^2 > c^2$ easily: simply set $w > 1$ in the macroscopic description, i.e., presume that $p/c^2 > \rho > 0$. Then the speed of sound cones lie outside the speed of light cones in all directions[1] at all events, and fluid waves can propagate at speeds up to and including this superluminal speed of sound. Of course this is far from ordinary matter. It does not accord with anything so far experienced in the real world. But does it cause serious problems in terms of causal violations or Lorentz invariance, considered macroscopically?

Recently it has been claimed (e.g., Refs. [8,9,10,11]) that there need not be problems with either issue, if one approaches the problem in an open-minded way. The key point is the following: we usually associate causality with the light cone, but any suitable set of cones can be used to define the macroscopic limiting speed, including sound cones that lie outside the light cones. Assuming that (1) the 4-velocity of the fluid defining the sound cone stays inside the light cone, and (2) photons and gravitons still move at the speed of light, then the light cones will always stay inside the sound cones and so will not give any acausal propagation in the sense defined by the sound cones. The basic essence of the relativistic causality requirement would be preserved, though causal limits would be determined by the speed of sound in the fluid rather than the speed of light.

Now, Lorentz invariance is broken by the sound cones in this case, because a change of the observer's velocity will result in apparently different speeds of sound in different directions (unlike the case of light, which has the same speed in all directions for all observers). This proposal might therefore appear to violate Einstein's basic principle that the laws of physics should be the same in all inertial frames. But we are concerned with solutions of the basic equations, rather than the symmetries of the equations themselves. All realistic fluid solutions break Lorentz invariance[2], in particular because of the uniquely defined 4-velocity of the matter, and these solutions are no exception. Equations can have an invariance not shared by their solutions.

Indeed these papers are not considering general superluminal motions, but superluminal signals referred to a specific rest frame. These signals are just as non-Lorentz-invariant as sound waves in normal fluids, which are subluminal with respect to the rest frame of the fluid. A Lorentz transformation which preserves the light cone will not in general preserve either subluminal or superluminal signals

[1] A perfect fluid is isotropic about its fundamental velocity u^μ, so that relative to this velocity the speed of sound is the same in all directions.

[2] The fluid stress tensor is only Lorentz invariant if $\rho + p/c^2 = 0$, but this is just the degenerate case of a cosmological constant. It is not a realistic fluid, and in any case cannot support matter perturbations.

of this sort, because it will not preserve the 4-vector on which the sound cone is based. However, the rest frame of the fluid and the sound velocity in it may be physically well-defined, just as the rest frame in cosmology is defined by the 4-velocity of the substratum. No physical violation is involved in this aspect of the proposal. Lorentz-invariant theories not only can have, but to model some aspects of reality must have, non-Lorentz-invariant solutions (otherwise normal sound waves would not be allowed either). The invariance then maps one solution to another different one, rather than to itself.

In other observers' rest frames, in this case, causal limits will again be determined by the speed of sound cone of the fluid rather than the light cone. There is no way to send a signal into one's past provided no signal, and no observer, travels outside the sound cone, so this cone is itself the causal limit cone. The argument is exactly the same as usual causality, just with different cones: the cause of a here-and-now event must lie inside the past sound cone and this cannot be reached from the future sound cone. The cones are fixed and the same for all observers. Thus causal paradoxes do not arise from this effect, because these cones are fixed by the invariant fluid velocity; they are not arbitrarily assignable by changing the observer's velocity.

From the viewpoint of standard relativity theory, a major problem with this model is that *causality depends on the matter content of the universe.* In the usual view, the same causality applies to all physics, independent of the kind of matter present; the causal limit has a much more fundamental character. In the proposal discussed here, the notion of a causal limit becomes arbitrarily dependent on the matter model, unlike the relativistic proposal where it is the same for all matter. Furthermore, according to the simplistic model discussed here, arbitrary fluids could give arbitrarily large values for c_s; there is no longer any effective limiting speed at macroscopic scales.

Comment 2: *Lorentz invariance* per se *does not prohibit macroscopic theories with superluminal sound: the speed of sound could limit causality rather than the speed of light doing so. However this does not give a good theory of relativistic type since* (*a*) *causality depends on the matter model, and* (*b*) *there is then no upper limiting causal speed: any speed is apparently possible.*

One can reconcile these ideas only if there is some unique field that defines causality, and somehow all other fields are prevented from having a faster wave speed – i.e., a very special kind of matter or field exists that somehow has a fundamental role to play in all of physics. In the standard view, that role is played by the metric tensor. If there is another such field, it should be identifiable. Below we return to the issue of whether one can meaningfully define other metric tensors associated with the new proposal given here for limiting speeds.

3 Scalar fields and variational principles

A fluid description is of course a highly simplified effective theory, and one can propose more fundamental theories for the matter. The most common one in cosmology is a scalar field. If the Lagrangian density is $\mathcal{L}$, then the pressure and energy density (in the natural frame, $u_\mu \propto \partial_\mu\varphi$) are given by [14]

$$p = c^2\mathcal{L}\,,\ \rho = 2X\mathcal{L}_{,X} - \mathcal{L} \text{ where } X \equiv \frac{1}{2}g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi\,. \tag{2}$$

Fluctuations of the scalar field propagate with effective speed of sound [14]

$$c_s^2 = \frac{p_{,X}}{\rho_{,X}}\,. \tag{3}$$

A standard scalar field has Lagrangian density

$$\mathcal{L} = -X - V(\varphi)\,, \tag{4}$$

so that

$$p = c^2(-X - V)\,,\ \rho = -X + V\,. \tag{5}$$

It follows from Eq. (3) that

$$c_s^2 = c^2\,, \tag{6}$$

independently of the scalar field's potential. This can be explained from the local special relativistic viewpoint by the fact that for high frequency waves only the $g^{\mu\nu}\nabla_\mu\nabla_\nu\delta\varphi$ terms in the wave equation for scalar field fluctuations are significant. Alternatively, using wave-particle duality, massive particles can move with any four-velocity inside the light cone, so that the limiting speed is c.

In the cosmological context, Eq. (5) and the Klein-Gordon equation imply

$$\frac{\dot{p}}{\dot{\rho}} = 1 + \frac{2V_{,\varphi}}{3H\dot{\varphi}} \,. \tag{7}$$

Clearly, $\dot{p}/\dot{\rho} \neq c_s^2/c^2$. Indeed, even in slow-roll inflation, when $\dot{p}/\dot{\rho} \approx -1$, we have $c_s^2 = c^2$. This difference between $\dot{p}/\dot{\rho}$ and c_s^2/c^2, unlike a perfect fluid with $\dot{p}/\dot{\rho} = w = c_s^2/c^2 =$ constant, reflects the presence of intrinsic entropy perturbations in the field [15].

Scalar fields with generalized, non-standard Lagrangians allow superluminal speeds of sound. For example, if we generalize Eq. (4) to

$$\mathcal{L} = -F(X) - V(\varphi) \,, \tag{8}$$

then Eqs. (2) and (3) give

$$\frac{c_s^2}{c^2} = \frac{F_{,X}}{F_{,X} + 2XF_{,XX}} \,. \tag{9}$$

Thus $c_s^2 > c^2$ is possible for appropriate choices of non-standard kinetic term $F(X)$. Examples include nonlinear complex scalar fields [12], k-essence models of inflation and dark energy [10,11], and Born-Infeld type models of scalar fields that supposedly can transmit information from inside a black hole [9].

The logic of these proposals is that any Lorentz-invariant Lagrangian leads to acceptable models. By contrast, if we do not give primacy to ad hoc matter models, but instead impose relativistic principles as fundamental [4,5,6], then the Lagrangian is ruled out as non-physical, since such scalar fields violate the most basic principles of special relativity theory.

Comment 3: *Existence of a variational principle does not necessarily imply existence of corresponding matter. If the solutions violate causality, this is* a priori *a good reason to believe that the variational principle is unphysical.*

Non-standard kinetic terms are highly problematic. There is no experimental evidence for them, and no compelling reason to think they are physical. As in the previous case, the notion of a causal limit becomes arbitrarily dependent on the matter model. As arbitrary scalar fields can give arbitrarily large values for the speed of sound, there is again no longer an effective limiting speed at macroscopic scales. Furthermore, the speed of sound can change in space or time from subluminal to superluminal or vice versa, as in k-essence models [4]. All these seem problematic from a relativistic viewpoint.

4 Alternative metrics

The sound cones for any given fluid or scalar field can be represented by an appropriate metric tensor of hyperbolic type. If u^μ is the matter 4-velocity, and $h_{\mu\nu} = g_{\mu\nu} + u_\mu u_\nu$ projects into the rest space at each event, then one can define the metric

$$(G^{-1})^{\mu\nu} = g^{\mu\nu} - (c^2 - c_s^2)h^{\mu\nu} \,, \tag{10}$$

which gives the characteristic cones, and the rays are given by

$$G_{\mu\nu} = g_{\mu\nu} + \frac{c^2}{c_s^2}(c^2 - c_s^2)h_{\mu\nu} \,. \tag{11}$$

Thus the sound cones are given by this metric, and it is useful for visualization purposes to draw them; they will lie outside the light cones when $c_s^2 > c^2$. One can then rephrase the point by saying that there are two metrics: in the case of superluminal sound those metrics agree that the interior of the light cone consists of timelike vectors.

However, some of those who argue that there is no problem with causality go much further: they say that if there is a superluminal mode, one can just re-define the physical metric to be the sound metric, Eq. (11), based on the pathological wave equation, and then the problem disappears. For example, Ref. [8] encapsulates this view by stating that: "causality should not be expressed in terms of the chronology induced by the gravitational field ... there is no clear reason why a metric or chronology should be preferred to the other ... the gravitational metric field is just one particular field on spacetime and there is no clear reason why it should be favored".

We profoundly disagree. The spacetime metric is special, despite these claims: it determines time measurements and spatial distances, as well as the free-fall motion that is the essential basis of the equivalence principle, and hence the basis for identification of gravity as being expressed through space-time curvature [1,2]. It does so alike for all matter and fields. Furthermore, if we abandon the spacetime metric as arbiter of causality, then we could find that the sound metric was in some places superluminal and in others subluminal, so that, at least at some events and in some directions, part of the light cone could lie outside the sound cone. Then photons and gravitons could propagate acausally relative to the wave-equation metric (i.e., the one that "makes" the superluminal modes causal).

Comment 4: *Just defining something as a metric does not mean that it has all the properties of the preferred spacetime metric. The spacetime metric is preferred in terms of clock measurements and free fall (geodesic) motion (including light rays), thus underlying General Relativity's central theme of gravity being encoded in spacetime curvature. It is also related to the Lorentz group that underlies all particle physics, and hence to the limiting speed of motion of all particles following from the special relativistic equations of motion at each point.*

The speed of sound metric simply does not have all these properties. It is in no way equivalent to the spacetime metric. And because of the relation to the Lorentz group and hence to special relativity, it is the speed of light cones that will represent correctly the microscopic limiting speed.

5 Microscopic fluid models

The spacetime metric defines the Lorentz transformations that underlie microscopic physics, and indeed is the basis of the definitions of variables that occur in current fundamental theories. The resulting special relativistic microscopic equations of motion prevent any real physical particle or associated signal moving faster than light; relativity only allows particles travelling at up to the speed of light (they cannot be accelerated to greater speeds because of the unbounded increase of the relativistic inertial mass). And here is the real problem for any macroscopic theory of superluminal signal propagation: you cannot base it in a microscopic theory of matter consistent with special relativity theory, because there is no underlying microscopic mechanism that could support such macroscopic behaviour. In essence: you cannot have macroscopic signals propagating at a high speed on the basis of particles and fields all of which travel at a slower speed.

As stated in Ref. [4] in relation to scalar fields: "The idea is of course that φ is an effective low energy degree of freedom of some fundamental high energy theory which should satisfy basic criteria: among them, most importantly, Lorentz invariance and causality. No information should propagate faster than the speed of light $c = 1$." Now if this is true of the microscopic theory underlying the macroscopic theory, it has to be true of the macroscopic theory as well. Any superluminal signals would have to be mediated by particles travelling faster than light, but such particles do not exist. More generally, the low-energy effective theory, if it is to have a high-energy completion that satisfies the basic postulates of quantum field theory, will not admit superluminal signals [5].

There are circumstances in which microscopic theory supports effects which can be apparently superluminal. Some of these arise within quantum field theory.[3] Quantum entanglement effects can link spacelike-separated events and in that sense work superluminally – but such effects depend on careful state preparation and are so fragile that they cannot be causally effective on macroscopic scales. They seem unable to carry arbitrarily chosen information faster than light, which a genuine wave is able to do. For the matter model discussed in [12] the superluminality is identified in [13] as originating in renormalization of a negative bare mass and gives rise to kinetic energies with no lower bound (and

[3] Although Feynman diagrams can be thought of as including particles travelling backwards in time, we do not accept the interpretation that one can therefore send macroscopic physical signals backwards in time via such effects or via virtual particles.

hence without a well-defined ground state). In [16] the superluminal velocities which are found in the Scharnhorst effect (where they are due to QED corrections in the Casimir effect) are argued not to lead to causality violations because they define a causal cone in the frame of the Casimir plates which can used to redefine causality in the same way as the sound cones discussed above; however, they exist only locally between the plates and therefore cannot be used to signal. It is also possible to construct lattice models with $p > \rho c^2$ and $dp/d\rho > c^2$, but the sound speed (i.e. the signal propagation speed) remains subluminal [17].

There are also effects arising in the case of light itself from quantum mechanical tunnelling. These have been observed and it has been argued [18] that they are essentially the same as the effects seen for "X-shaped" light beams, although the latter can be described by classical field theory (see e.g. [19]). These two effects have generated an extensive literature. However, strong counterarguments have been given against both the accuracy of some of the experiments and their theoretical interpretation [20, 21]: in particular the X-shaped beam effects have been argued to be due to a "scissors effect" where the point at which two beams interfere constructively moves at superluminal speed [22], an effect similar to the possible "superluminal" movement of the end of a beam from a lighthouse. Even those active in working on these waves do not unambiguously argue that they lead to superluminal propagation of information or signals [19, 23].

The X-shaped beams can be discussed in terms of a dispersion relation, and one then has the well-known issues of distinguishing the phase velocity, the group velocity, and the signal velocity: dispersion is in fact common in the acoustics of media less simple than the models discussed above. For example, in the X-shaped beams, the peak may be travelling at a group velocity, apparently superluminally, although the leading edge travels at the phase speed c – but this is only possible until the peak catches up with the front [22]. One can have superluminal group velocities, but this does not lead, in any physically plausible example we know of, to speeds of sound greater than those of light (see e.g. Ref. [24])[4].

Thus it appears that none of these examples provides a convincing contradiction to the principle that if the microscopic theory has a limiting speed, that of light, then so does any macroscopic theory based on it. You can send signals at the speed of light, characterized by the light cones in the usual way, but no faster. Thus causality for all particles is associated with these specific cones. Although you can create macroscopic descriptions of material with superluminal signals, as discussed in the preceding sections, you cannot adequately base them in a microscopic theory that obeys fundamental requirements of theoretical physics. Indeed the limiting state one can conceivably get from a viable microscopic description is apparently "stiff matter" as proposed by Zeldovich [25], with equation of state $p/c^2 = \rho$, so that $c_s^2 = c^2$.

Comment 5: *It appears that none of the above causality-violating theories can be based on a microscopic matter model that obeys special relativity principles. A viable theory of causal limits must be a consistent whole for microscopic and macroscopic physics. The extremely well-tested theory of special relativity then insists on the speed of light as the local limiting speed of causality.*

6 Conclusion

As in the case of varying speed of light theories (see, e.g., Ref. [26] for a discussion), one must take physics as a whole into account whenever proposing theories of superluminal speed of sound; one cannot just tinker with some part of physics without thinking of the consequences for the whole. Special relativity is one of the best tested theories we have. It is not enough to put forward *ad hoc* matter models that violate its principles and effectively alter all of physics. In order to make a serious challenge of this nature, one needs a solid justification, and a really plausible reason to abandon it – backed up (in due course) by experimental data.

[4] It appears that one can also analyze this situation, and that of entanglement, using the information-theoretic interpretation of entropy, and again reach the conclusion that superluminal propagation is not possible. We thank G. Thompson for raising this point.

We have strongly made the case for a particular viewpoint based on an understanding of present day physics. However it is always possible that this understanding could be contradicted by experiment and observation.[5] In that case, theory must give way to data.

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[5] For example, it is in principle possible to test the speed of sound of dark energy in the universe by observations of supernova luminosity distances, weak lensing and anisotropies in the cosmic microwave background.